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UNITED STATES DEPARTMENT OF THE INTERIOR

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IMPROVEMENTS IN HEAP LEACHING TO RECOVER SILVER AND GOLD FROM LOW-GRADE RESOURCES

by

G. E. McClelland[1] and J. A. Eisele[2]

ABSTRACT

As part of its mission to assure an adequate domestic supply of metals essential to the Nation's welfare, the U.S. Department of the Interior, Bureau of Mines, investigated a particle agglomeration technique as a means for improving the flow of leaching solution through heaps of clayey or finely crushed, low-grade, gold-silver ores. Bench- and pilot-scale experiments showed that the percolation rate of cyanide leaching solution was markedly enhanced by mixing the ore with a portland cement binder, moistening the mixture, and mechanically agglomerating and aging the feed prior to heap building and leaching. The rate of gold and silver recovery markedly increased because of the increased, uniform percolation of leaching solution through the agglomerated feed. The use of concentrated cyanide solution instead of water during the agglomeration procedure decreased the leaching time required to obtain maximum recovery. Results of bench- and pilot-scale experiments are discussed.

INTRODUCTION

Exploration during the past few years has identified numerous low-grade, gold-silver deposits throughout the western United States. Recent increases in gold and silver prices have generated interest in processing these low-grade ores by heap leaching. Heap leaching with cyanide solution has potential application to many of these low-grade materials. For heap leaching to be successful, the material must maintain good permeability after being stacked into heaps, so that the leaching solution percolates evenly throughout the heaps.

Segregation of fine and coarse particles occurs during stacking of dry feed on a heap and additional segregation occurs during leaching of the heap. The permeability and porosity problems that occur during leaching are caused by the segregation of the minus 100-mesh material. To avoid these problems,

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the very fine ore must be uniformly distributed throughout the heap during stacking.[3] [4]

In an earlier publication,[5] the Bureau of Mines described the advantages of particle agglomeration as a pretreatment for certain materials that were difficult to treat by standard heap leaching techniques. Excessive clay or fines prevented uniform percolation flow of the leaching solution. Laboratory tests showed that the percolation flow rates of cyanide leaching solutions increased by mixing the ore with lime and water, mechanically agglomerating, and aging the mixture prior to heap leaching.

The objective of the present investigation was to investigate binders other than lime for particle agglomeration pretreatment and to transfer the technology to industry by cooperative pilot-scale studies.

LABORATORY EQUIPMENT AND MATERIAL

Investigations to determine the effectiveness of binders for the agglomeration of fine particles were carried out on 50-lb charges of material. A schematic of the laboratory column leaching apparatus used to simulate the effects of heap leaching is shown in figure 1. The plexiglass columns were 5 feet high and had an inside diameter of 5.5 inches. Four inches of washed sand and gravel enclosed in a basket container were placed in the column to prevent the ore from plugging the solution outlet. A 50-lb charge of material was placed on top of the supporting material and gave a bed height of about 4 feet. A three-way plastic discharge valve was used to measure the flow rate and take solution samples. The pregnant cyanide solution exiting the leaching column was pumped through three columns in series, each of which contained 30 grams of activated carbon to adsorb the gold and silver. Minus 6- plus 16-mesh coconut shell activated carbon was used for all gold and silver adsorption. The barren solution was recycled to the top of the column.

A process development unit (PDU) used the same arrangement of equipment as shown in figure 1 but the equipment was larger. The column, constructed of fiberglass reinforced plastic, was 2 feet in diameter and 16 feet high. A porous gravel bed supported the ore charge. Tests were conducted on 1.5-ton ore charges that filled the column to a height of 12 to 14 feet. Four carbon adsorption columns, each containing 5 lb of activated carbon, were used to adsorb the precious metals from the pregnant solution.

A 39-inch rotating disk pelletizer was used to mechanically agglomerate the feed for the columns. Binder and dry ore were mixed, put in the pelletizer, and a controlled amount of liquid added while the pelletizer was running. The agglomerated material was cured prior to leaching. After the

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[3]Chamberlin, P. D. Heap Leaching and Pilot Testing of Gold and Silver Ores. Min. Cong. J., v. 67, No. 4, April 1981, pp. 47-52.

[4]Johanson, J. R. Particle Segregation...And What to do About It. Chem. Eng., v. 85, No. 11, May 1978, pp. 183-189.

[5]Heinen, H. J., G. E. McClelland, and R. E. Lindstrom. Enhancing Percolation Rates in Heap Leaching of Gold-Silver Ores. BuMines RI 8388, 1979, 20 pp.

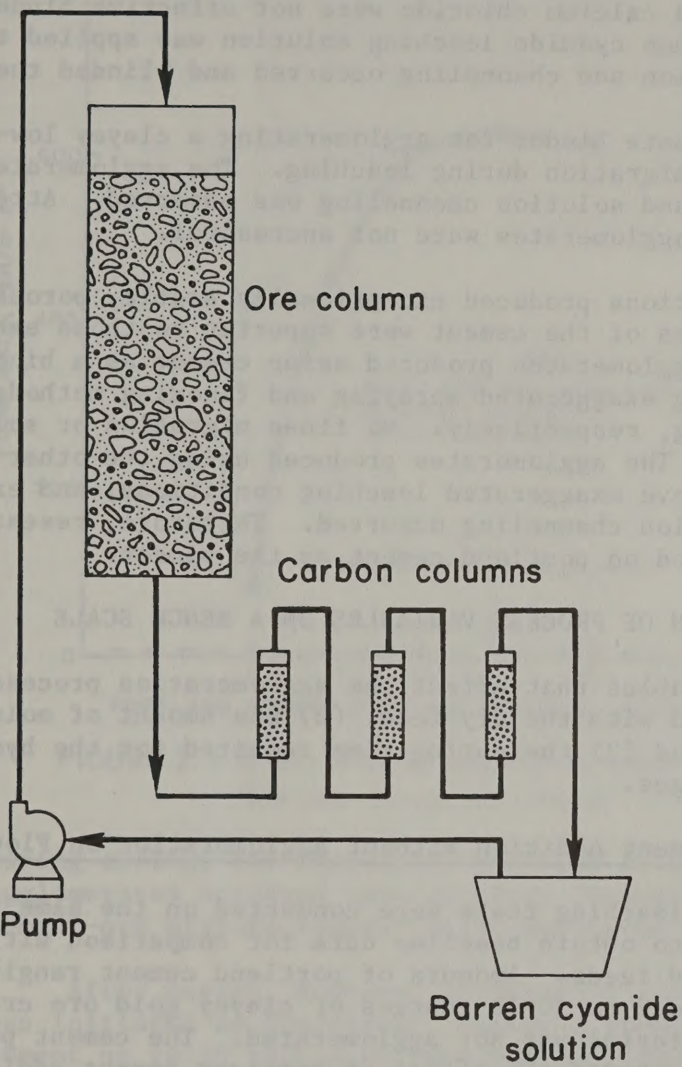

FIGURE 1. - Flow diagram for simulated heap leaching experiments.

curing period, usually 24 hr, the feed was placed in the column and leaching started by pumping solution into the top of the column. A layer of coco matting covered the surface of the ore bed to facilitate uniform leaching solution distribution.

Calculated head analyses and gold recoveries from each test were determined by the amount of gold adsorbed by the carbon, the amount remaining in the final pregnant solution, and the gold values remaining in the leached residue. All solid samples were assayed by conventional fire assay methods. Solution samples were analyzed by atomic absorption spectrophotometry.

INVESTIGATION OF BINDERS

Calcined lime was used in the laboratory investigations that led to the development of particle agglomeration pretreatment.[6] Lime was selected because it was used as a flocculant in thickening and dewatering applications, and is frequently used for protective alkalinity in conventional cyanidation. Lime reacted with the silicates contained in the clayey constituents of the ore during the aging period. Rigid but porous hydrated calcium-silicate bridges were produced that bound the fine particles together. The agglomerated particles were strong enough to withstand forces normally encountered during heap leaching, but were porous enough to allow adequate penetration and flow of cyanide leaching solution through the bedded ore.

As part of a continuing research effort to improve agglomeration pretreatment, binders other than lime were evaluated both with and without alkaline compounds to provide protective alkalinity during cyanidation. Binders investigated included magnesia, calcined dolomite, calcium chloride, and portland cement (type II). Type II is the portland cement most commonly used by the construction industry.

[6]Reference cited in footnote 5.

Calcined dolomite and calcium chloride were not effective binders. The agglomerates broke down when cyanide leaching solution was applied to the bedded ore. Fines migration and channeling occurred and blinded the heap.

Magnesia was an adequate binder for agglomerating a clayey low-grade gold ore and eliminated fines migration during leaching. The agglomerates produced were larger than desired and solution channeling was observed. Attempts to decrease the size of the agglomerates were not successful.

Portland cement additions produced exceptionally stable, porous agglomerates. Binding properties of the cement were superior to those exhibited by the other binders. The agglomerates produced using cement as a binder endured percolation leaching using exaggerated spraying and flooding methods to simulate heap and vat leaching, respectively. No fines migration or solution channeling was observed. The agglomerates produced using the other binders "broke down" under the above exaggerated leaching conditions, and excessive fines migration and solution channeling occurred. Therefore, research investigations were concentrated on portland cement as the binder.

INVESTIGATION OF PROCESS VARIABLES ON A BENCH SCALE

Three principal variables that affect the agglomeration process are (1) the amount of binder mixed with the dry feed, (2) the amount of moisture used to wet the dry mixture, and (3) the curing time required for the hydration of the calcium silicate bridges.

Effect of Portland Cement Addition Without Agglomeration on Flow Rate

Initial column heap leaching tests were conducted on the same clayey gold ore described in RI 8388 to obtain baseline data for comparison with data obtained from agglomerated feeds. Amounts of portland cement ranging from 0 to 20 lb/ton feed were added to 50-lb charges of clayey gold ore crushed to 3/8-inch size, but the material was not agglomerated. The cement provided protective alkalinity and showed the effect of portland cement addition without agglomeration. After mixing the cement with the dry feed, the mixture was placed in the leaching column, and the downward percolation leach was started using 12 liters of solution containing 2 lb of sodium cyanide per ton of solution. The leaching solution was recirculated through the system until no gold was detected in the pregnant solution. Flow-rate measurements were made daily for 5 days and averaged to determine the flow rate. Without agglomeration the percolation flow rate was independent of the amount of portland cement added to the dry feed, and remained constant at 0.12 gal/hr ft^2. The results are shown graphically as baseline data in figure 2, and represent conventional heap leaching of the clayey gold ore without agglomeration.

Effect of Portland Cement Addition With Agglomeration on Flow Rate

Fifty-pound charges of clayey gold ore crushed to 3/8-inch size were mixed with from 0 to 15 lb of portland cement per ton of feed. Water was added to the cement-ore mixture until the moisture content of the mixture on the pelletizer was 12 wt-pct. The wetted mixture was tumbled on the

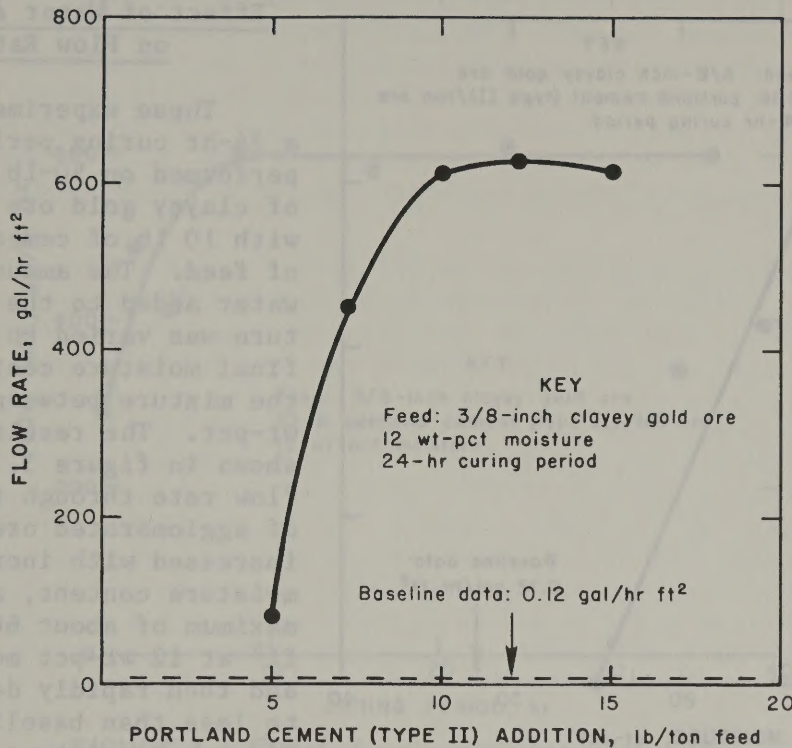

FIGURE 2. - Effect of binder addition on solution flow rate through the column.

pelletizer until the fine and clay material was agglomerated. Adequate mixing of the portland cement and water into the ore was important for successful agglomeration of the feed. During the agglomeration step, the fine particles adhered to the surface of the larger particles, thus, avoiding particle segregation. The fines coating the larger particles were porous enough so that cyanide solution could penetrate and dissolve the gold particles associated with the coarser material.

The agglomerated feed was placed in the leaching column and cured for 24 hr at ambient temperature. The column was capped to minimize drying of the pellets. If the pellets dried out during curing, the hydrolysis reaction stopped and partial breakdown of the agglomerates occurred upon wetting. Strong agglomerates are made if the cement-ore mixture remains moist during curing.

After curing, downward percolation leaching of the agglomerated material was initiated as described. Figure 2 shows that increasing the amount of cement up to 10 lb/ton of feed markedly improved percolation rates through the ore column. This amount of cement supplied the protective alkalinity required during leaching under normal heap conditions. No additional base was required to maintain the leaching solution pH at 11. Maximum flow-rate measurements were made after leaching of the gold was completed. The material in the column was flooded with leaching solution, and the rate at which the solution drained from the column was measured.

The high percolation flow rates obtained under flooded conditions would be impractical in an actual heap leaching operation because of solution pumping requirements, but the data demonstrate that very stable, porous agglomerates are produced that do not break down under exaggerated leaching conditions. The data indicate that vat leaching could be employed for leaching agglomerates made with portland cement.

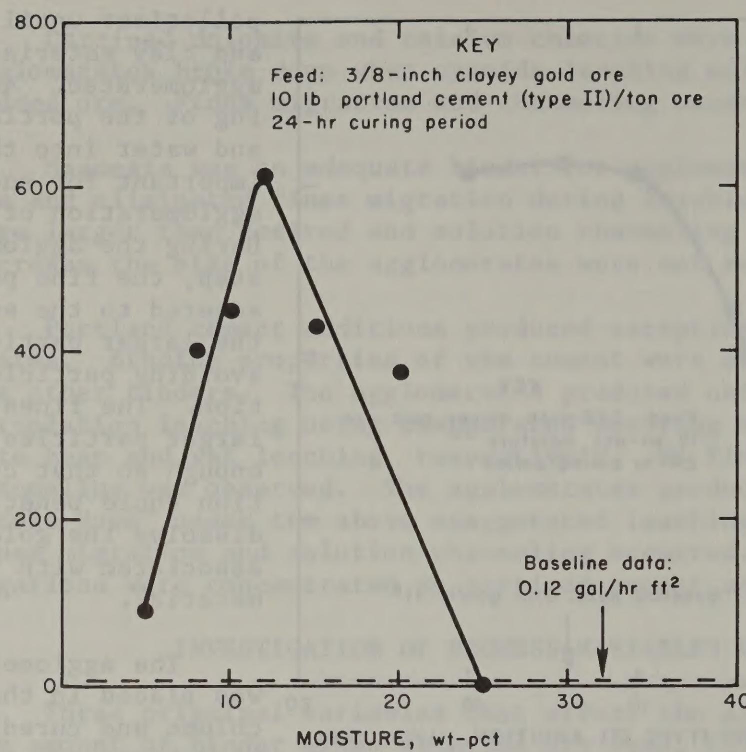

FIGURE 3. - Effect of moisture content on solution flow rate through the column.

Effect of Water Addition on Flow Rate

These experiments using a 24-hr curing period were performed on 50-lb charges of clayey gold ore mixed with 10 lb of cement per ton of feed. The amount of water added to the dry mixture was varied to bring the final moisture content of the mixture between 5 and 25 wt-pct. The results are shown in figure 3. Solution flow rate through the column of agglomerated ore increased with increasing moisture content, attained a maximum of about 600 gal/hr ft^2 at 12 wt-pct moisture, and then rapidly decreased to less than baseline at 25 wt-pct moisture. These data show that the permeability of the agglomerated feed is dependent upon the amount of water employed in the agglomeration step. If too much water is added, the feed-cement mixture becomes a mass of mud, and does not form agglomerates. Figure 3 shows that the best moisture content for agglomerating the ore is 12 wt-pct. However, moistures from 8 to 16 wt-pct produce acceptable agglomerates.

Effect of Curing Time on Flow Rate

A series of column leaching experiments was conducted to determine the effect of curing time on the percolation flow rates. Fifty-pound charges of clayey gold ore were mixed with 10 lb of portland cement per ton of ore, wetted with 12 wt-pct water, and agglomerated on the disk pelletizer. The agglomerated charges were cured for 0, 2, 4, 8, 16, 24, and 36 hr at ambient temperature in capped leaching columns. Flow rates are presented in figure 4.

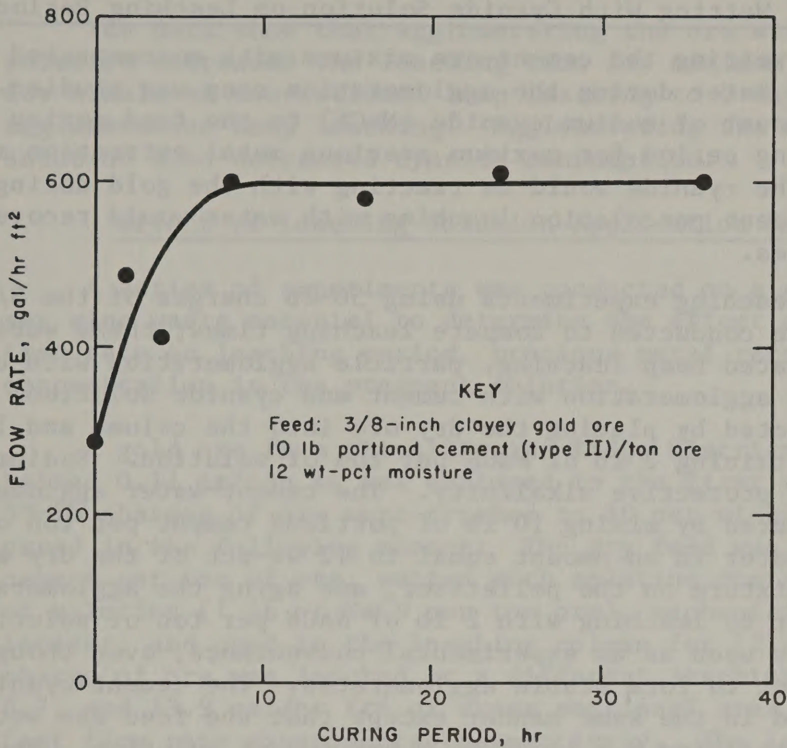

FIGURE 4. - Effect of curing period on solution flow rate through the column.

The data show that the duration of the curing process is an important operating parameter up to 8 hr, but no further improvement in flow rate occurred after 8 hr. When lime was used as a binder, the minimum curing time to achieve stable agglomerates was 24 hr.

The best combination of portland cement, water, and curing time determined experimentally for the clayey gold ore is summarized in table 1. Agglomeration pretreatment increased the percolation rate from 0.1 to 610 gal/hr ft^2 of cross sectional area, a 6,100-fold increase in percolation. Gold extraction was determined during the simulated heap leaching sequence. The 70-pct extraction obtained was the same as that obtained by agitation bottle leaching tests of 3/8-inch feed material.

TABLE 1. -Summary of experimental results on clayey gold ore

Best pretreatment conditions:	
Portland cement....................lb/ton of ore..	10
Moisture...................................wt-pct..	12
Curing time.....................................hr..	8
Percolation rates,[1] gal/hr ft^2:	
Baseline, no pretreatment..........................	0.1
With best pretreatment.............................	610.0
Gold extraction....................................pct..	70

[1]Percolation rate measurements were taken under flooded column conditions.

Effect of Wetting With Cyanide Solution on Leaching Period

The effect of wetting the cement-ore mixture with concentrated cyanide solution instead of water during the agglomeration step was studied. By adding the required amount of sodium cyanide (NaCN) to the feed during agglomeration, the leaching period for maximum precious metal extraction might be decreased because the cyanide would be reacting with the gold during the curing period. Subsequent percolation leaching with water would recover the dissolved gold values.

Three column leaching experiments using 50-lb charges of the 3/8-inch clayey gold ore were conducted to compare leaching times; these were: baseline-unagglomerated heap leaching, particle agglomeration with cement and water, and particle agglomeration with cement and cyanide solution. The baseline test was conducted by placing the dry ore into the column and leaching with a solution containing 2 lb of NaCN per ton of solution. Sodium hydroxide (NaOH) was used for protective alkalinity. The cement-water agglomeration experiment was prepared by mixing 10 lb of portland cement per ton of dry ore, wetting with water in an amount equal to 12 wt-pct of the dry mixture,[7] agglomerating the mixture on the pelletizer, and aging the agglomerated material for 24 hr prior to leaching with 2 lb of NaCN per ton of solution. A 24-hr curing period was used as an experimental convenience, even though an 8-hr period was sufficient to form stable agglomerates. The cement-cyanide agglomerates were prepared in the same manner except that the feed was wetted with a cyanide solution containing 8.6 lb of NaCN per ton of solution. The ratio of cyanide to ore, based on cyanide concentration of the pretreatment solution, was the same as the cement-water agglomeration experiment--1 lb of NaCN per ton of ore. Water content of the cyanide solution added was 12 wt-pct of the dry mixture. Leaching was started with water rather than cyanide solution. Results from these experiments are shown in table 2.

TABLE 2. - Column leaching data for clayey gold ore

	No pre-treatment (baseline)	Particle agglomeration with--	
		Cement and water	Cement and cyanide solution
Calculated head, oz/ton:			
Gold	0.09	0.10	0.10
Silver	0.47	0.30	0.40
Portland cement......lb/ton of ore..	0	10	10
Cyanide.........lb/ton of solution..	2	2	[1]8.6
Moisture....................wt-pct..	0	12.0	12.0
Percolation rate........gal/hr ft^2..	0.1	610.0	600.0
Leaching period...............days..	26	9	5
Cyanide consumption..lb/ton of ore..	1.0	0.8	0.6
Recovery, pct:			
Gold	68.1	70.3	73.6
Silver	15.6	26.7	31.0

[1]Based on cyanide concentration of the pretreatment solution; total amount of cyanide added per ton of ore was the same for all tests.

[7]Throughout this report, moisture contents are expressed as weight percents of the dry mixture.

The data show that agglomerating the ore with cement and strong cyanide solution decreased the leaching time for maximum gold extraction from 26 days for simulated conventional heap leaching to 5 days for cyanide solution agglomeration heap leaching. Agglomerating the ore with cyanide leaching solution also decreased cyanide consumption.

Effect of Leaching Solution Application Rate on Leaching Period

A series of experiments was conducted on a gold ore and on a clayey silver mine waste material to determine the effect of leaching solution application rate on leaching period, precious metal recovery, and precious metal concentration in the pregnant solution.

A gold ore from the Alligator Ridge District in eastern Nevada that contained 0.11 oz/ton Au was employed in the first series of experiments. Three 50-lb charges of ore were crushed to 80 pct minus 3/8 inch and were all prepared in the following manner: The dry feed was mixed with 10 lb of portland cement per ton of ore, wetted with solution containing 13 lb of NaCN per ton of solution (1 lb of NaCN per ton ore), mechanically agglomerated on the pelletizer, and aged in the leaching column for 72 hr prior to leaching. Each charge of ore was leached at a different leaching solution flow rate of 0.9, 5.7, and 13.9 gal/hr ft^2 of cross sectional area, for the slow, moderate, and fast flow rate experiments, respectively. The leaching apparatus shown in figure 1 was used with one modification. A pregnant solution reservoir was added to measure the volume of each increment of pregnant solution coming from the column. Samples for analysis of contained gold values were also withdrawn from the solution in the reservoir. After adsorption on activated carbon the barren solution was recycled to the leaching column. Conducting experiments in this manner enabled the calculation of an accurate leaching rate profile.

The effect of flow rate on leaching period and gold recovery is shown in table 3. The data show that gold may be recovered in a significantly shorter leaching period using the fast solution flow rate.

TABLE 3. - Effect of leaching solution flow rate on precious metal recovery and leaching period

Solution flow rate, gal/hr ft^2	Leaching period, hr	Recovery, pct
Gold:		
Slow (0.9)....................	125	66.6
Moderate (5.7)...............	95	83.9
Fast (13.9)..................	18	90.0
Silver:		
Slow (0.6)....................	125	59.0
Moderate (5.2)...............	80	68.0
Fast (16.4)..................	55	76.5

Figure 5 graphically illustrates the effect of leaching solution application rate on the cumulative gold recovery and leaching period. If the data in figure 5 are extrapolated, gold recovery of 90 pct can be expected in 160 hr and in 400 hr of leaching with the moderate and slow application rates, respectively. Maximum gold recovery for this ore by agitation bottle leaching was 91 pct for 3/8-inch material.

There was concern that increasing the leaching solution application rate would severely dilute the gold concentration of the pregnant effluent. Figure 6 illustrates the effect of solution flow rate on gold concentration in the pregnant solution with time. The data show that the gold concentrations in the moderate and fast solution application rate experiments were less than in the slow test; however, not significantly less to render the overall leaching rate impractical.

A similar series of experiments was conducted using an extremely clayey silver waste material containing 2.3 oz/ton Ag. Three 50-lb charges of ore crushed to 80 pct minus 3/8 inch were agglomerated using 10 lb of portland cement per ton of ore, wetting with solution containing 11.8 lb of NaCN per ton to give 8.8 wt-pct moisture content, mechanically agglomerating on the pelletizer, and aging for 72 hr prior to leaching. The different leaching solution application rates used were 0.6, 5.2, and 16.4 gal/hr ft^2 in the slow, moderate, and fast solution application rate experiments, respectively. Leaching procedures were the same as those described in the previous example. The effect of solution application rate on leaching period and silver recovery for the silver-bearing waste material is shown in table 3.

The data show a similar effect on silver recovery and leaching period as for the gold ore in the previous example. Figure 7 graphically illustrates the effect of leaching solution application rate on silver recovery and leaching period. The ultimate silver recovery, regardless of solution application rate, would be 76.5 pct. The slower the solution is applied, the longer the leaching period required.

Extrapolating the data in figure 7 to a maximum silver recovery of 76.5 pct shows that 365 hr and 1,100 hr are required for the moderate and slow rates, respectively.

The effect of solution application rate on silver concentration in the pregnant solution was similar to that in the previous gold sample. Figure 8 illustrates this trend.

The rate at which leaching solution is applied to the agglomerated feed has a pronounced effect on the leaching period required to obtain maximum precious metal recovery. These data are valid for a feed material that has been mixed with a portland cement binder, moistened with a strong cyanide solution, and aged prior to leaching.

Other Bureau of Mines research[8] has shown that the precious metal leaching rate is independent of leaching solution application rate on a feed material that has not been pretreated in a cyanide solution.

[8]Potter, G. M. Recovering Gold From Stripping Waste and Ore by Percolation Cyanide Leaching. BuMines TPR 20, 1969, 5 pp.

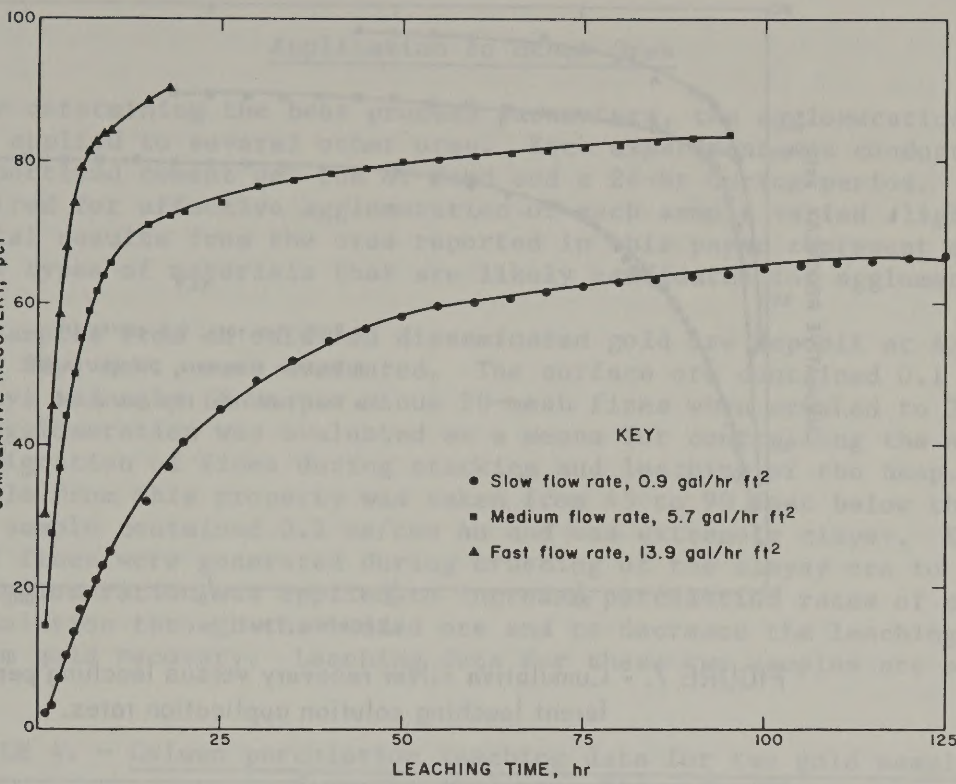

FIGURE 5. - Cumulative gold recovery versus leaching period at different leaching solution application rates.

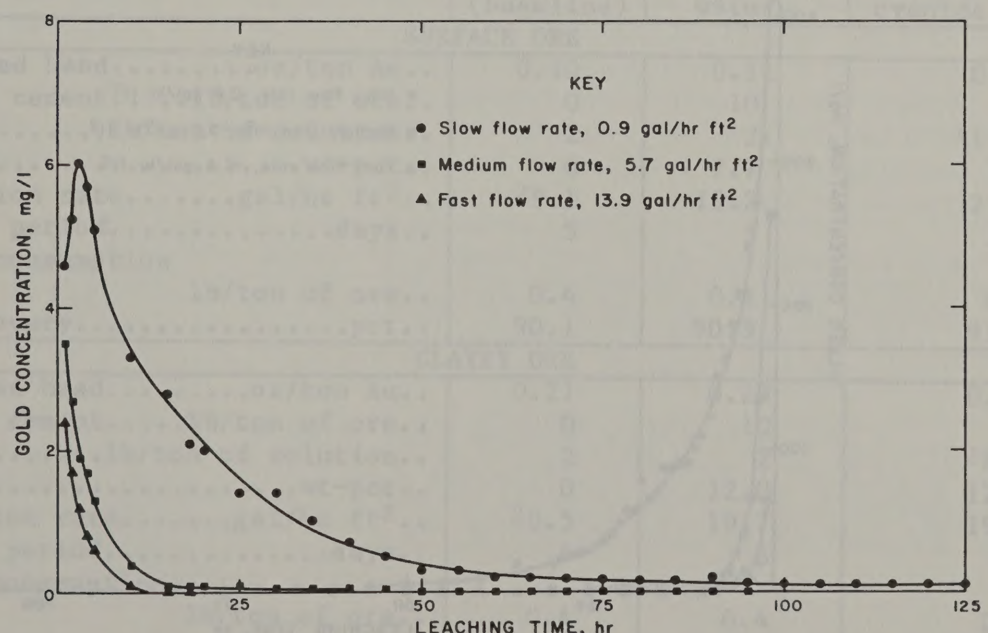

FIGURE 6. - Effect of solution flow rate on gold concentration in pregnant solution with time.

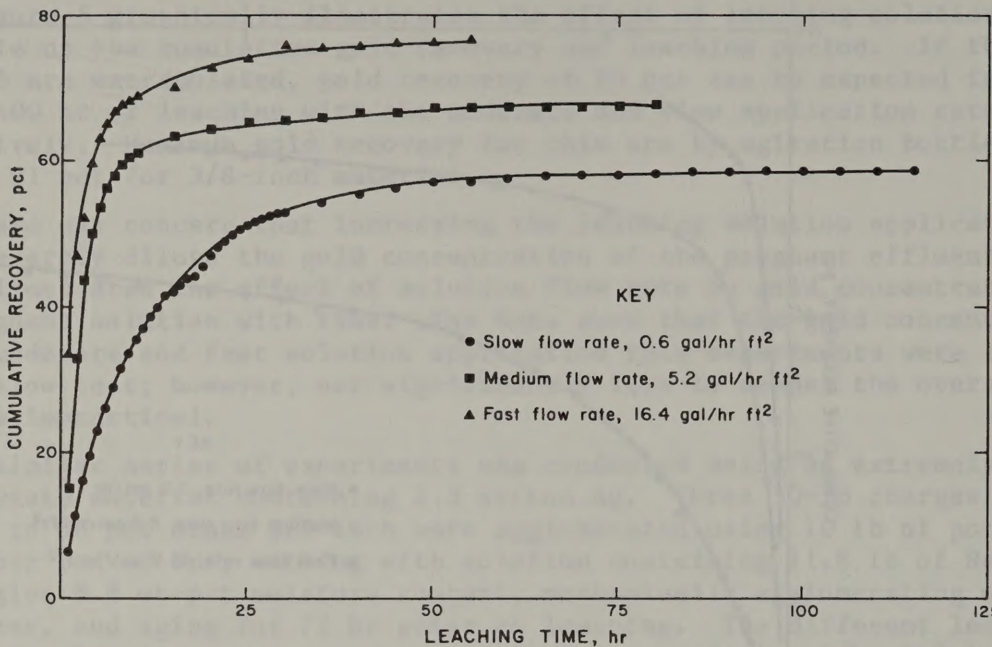

FIGURE 7. - Cumulative silver recovery versus leaching period at different leaching solution application rates.

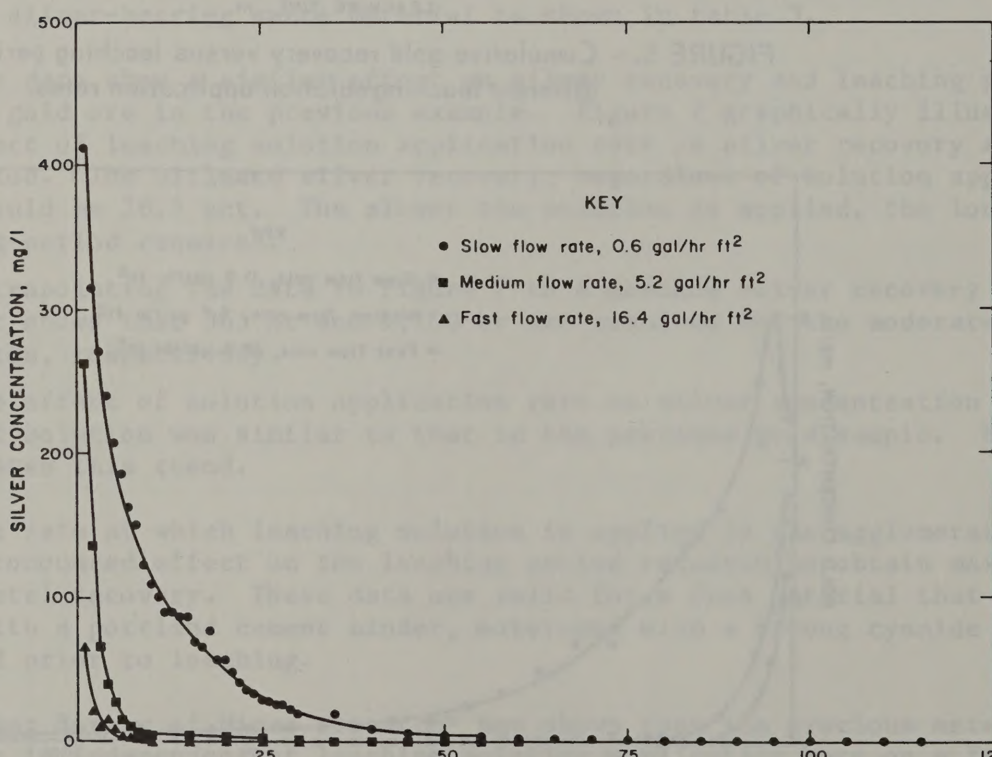

FIGURE 8. - Effect of solution application rate on silver concentration in pregnant solution with time.

Application to Other Ores

After determining the best process parameters, the agglomeration technique was applied to several other ores. Each experiment was conducted using 10 lb of portland cement per ton of feed and a 24-hr curing period. The moisture required for effective agglomeration of each sample varied slightly. Experimental results from the ores reported in this paper represent a cross section of types of materials that are likely candidates for agglomeration.

Two samples from an oxidized disseminated gold ore deposit at Alligator Ridge near Ely, Nev., were evaluated. The surface ore contained 0.1 oz/ton Au, no clays and only 15 wt-pct minus 20-mesh fines when crushed to 3/8-inch. Particle agglomeration was evaluated as a means for controlling the segregation and migration of fines during stacking and leaching of the heap. The other sample from this property was taken from 45 to 90 feet below the surface ore. The sample contained 0.2 oz/ton Au and was extremely clayey. Excessive amounts of fines were generated during crushing of the clayey ore to 3/8 inch. Particle agglomeration was applied to increase percolation rates of cyanide leaching solution through the bedded ore and to decrease the leaching time for maximum gold recovery. Leaching data for these two samples are shown in table 4.

TABLE 4. - Column percolation leaching data for two gold samples from the Alligator Ridge deposit

	No pretreatment (baseline)	Particle agglomeration with-- Cement and water	Cement and cyanide solution
SURFACE ORE			
Calculated head.........oz/ton Au..	0.10	0.11	0.11
Portland cement.....lb/ton of ore..	0	10	10
Cyanide........lb/ton of solution..	2	2	[1]13.5
Moisture..................wt-pct..	0	7.7	7.7
Percolation rate.......gal/hr ft^2..	[2]9.1	19.2	21.1
Leaching period.............days..	5	5	1.5
Cyanide consumption lb/ton of ore..	0.4	0.4	0.3
Gold recovery.................pct..	90.1	90.9	91.0
CLAYEY ORE			
Calculated head.........oz/ton Au..	0.21	0.23	0.23
Portland cement.....lb/ton of ore..	0	10	10
Cyanide........lb/ton of solution..	2	2	[1]8.7
Moisture..................wt-pct..	0	12.0	12.0
Percolation rate.......gal/hr ft^2..	[2]0.5	19.7	19.5
Leaching period.............days..	9	5	2
Cyanide consumption lb/ton of ore..	0.4	0.4	0.3
Gold recovery.................pct..	90.6	91.2	91.4

[1]Cyanide content of the pretreatment solution; total cyanide per ton of ore was the same for all samples.

[2]Baseline-unagglomerated experiment flow rate measurements taken under flooded column conditions.

The data show that heap leaching was very effective in extracting gold from both of the samples. The data also show that particle agglomeration was not required for an adequate percolation rate in the surface ore sample. However, particle agglomeration with portland cement and cyanide solution decreased the leaching time; thereby increasing the production rate and, to a small extent, cyanide consumption in both samples. It should be noted that the effects of the inevitable particle segregation that occur in actual field operations are difficult to simulate in laboratory column leaching tests. For this reason, the beneficial results of agglomeration shown in table 4 are regarded as minimal compared to those that would be obtained in the field.

A gold ore from northern Idaho containing 0.06 ounce of gold per ton and trace amounts of silver was evaluated. The extreme clay content of the 3/8-inch feed material and the low natural pH of the wetted ore made gold recovery by conventional heap leaching impractical. Particle agglomeration effectively increased the percolation rate of leaching solution from 0.05 to 4.2 gal/hr ft^2, and markedly decreased the leaching time from 31 to 5 days when cyanide solution was used in agglomeration. Particle agglomeration with portland cement and cyanide solution also decreased cyanide consumption from 3.1 to 2.6 lb of NaCN per ton of ore. Results of these experiments are shown in table 5.

TABLE 5. - Column percolation leaching data for a gold ore from Idaho

	No pre-treatment (baseline)	Particle agglomeration with--	
		Cement and water	Cement and cyanide solution
Calculated head.........oz/ton Au..	0.06	0.06	0.06
Portland cement.....lb/ton of ore..	0	10	10
Cyanide........lb/ton of solution..	2	2	[1]10.4
Moisture...................wt-pct..	0	10.0	10.0
Percolation rate[2]......gal/hr ft^2..	0.05	4.16	4.23
Leaching period..............days..	31	15	5
Cyanide consumption lb/ton of ore..	3.1	3.0	2.6
Gold recovery.................pct..	85.6	88.3	91.7

[1]Cyanide content of the pretreatment solution; total cyanide per ton of ore was the same for all samples.
[2]Flow rate measurements taken under flooded conditions.

A high-clay silver-bearing mine waste material from the Rochester mining district near Lovelock, Nev., was subjected to the particle agglomeration technique. The waste material contained approximately 2.3 oz/ton Ag. Results from this series of experiments are shown in table 6.

TABLE 6. - Column percolation leaching data for a silver mine waste material from Nevada

	No pre-treatment (baseline)	Particle agglomeration with--	
		Cement and water	Cement and cyanide solution
Calculated head.........oz/ton Ag..	2.3	2.4	2.3
Portland cement.....lb/ton of ore..	0	10	10
Cyanide........lb/ton of solution..	2	2	[1]12.0
Moisture..................wt-pct..	0	9.6	8.8
Percolation rate[2]......gal/hr ft^2..	0.1	550.0	500.0
Leaching period.............days..	30	15	8
Cyanide consumption lb/ton of ore..	0.9	0.9	1.0
Silver recovery...............pct..	73.8	75.4	78.3

[1]Cyanide content of the pretreatment solution; total cyanide per ton of ore was the same for all samples.
[2]Flow rate measurements taken under flooded conditions.

The data show that particle agglomeration effectively increased the percolation flow rate, and decreased the leaching time required for maximum silver recovery. Particle agglomeration was not effective in decreasing the cyanide consumption, partially because the waste material contained cyanicides. The waste material was employed in pilot-scale tests which are described later in this paper.

The final sample evaluated was a low-grade oxidized silver ore from the Tonopah Divide mining district south of Tonopah, Nev. The ore contained 1.4 oz/ton Ag and 0.02 oz/ton Au. Approximately 65 pct of the silver and 75 pct of the gold were recoverable by direct agitation cyanide leaching; however, the ore was too low-grade to support the costs of conventional cyanidation. The ore was also too clayey to apply conventional heap leaching techniques.

Four column leaching experiments were conducted on the ore crushed to 80 pct minus 3/8-inch: baseline-conventional heap leaching, particle agglomeration with cement and water, particle agglomeration with cement and cyanide solution, and particle agglomeration with cement and cyanide solution using a simulated vat leaching technique. The feed material for each experiment was prepared as previously described. The simulated vat leaching experiment was conducted by repeatedly flooding and soaking the agglomerated feed material with leaching solution. After 24 hr the leaching solution was drained and passed through three columns each containing 30 grams of activated carbon. The resultant barren cyanide leaching solution was recycled to the leaching column for additional contact with the agglomerated feed. Results from these experiments are shown in table 7.

TABLE 7. - Column percolation leaching data for Tonopah Divide silver ore

	No pre-treatment (baseline)	Particle agglomeration with--		
		Cement and water	Cement and NaCN	Cement and NaCN (vat leaching)
Calculated head, oz/ton:				
Gold	0.02	0.02	0.02	0.02
Silver	1.4	1.2	1.4	1.3
Portland cement lb/ton of ore	0	10	10	10
Cyanide...lb/ton of solution	2.0	2.0	[1]12.0	[1]12.0
Moisture...wt-pct	0	8.8	8.8	8.8
Percolation rate..gal/hr ft^2	[2]0.06	18.4	19.75	[2]414.9
Leaching period...days	23	23	23	23
Cyanide consumption lb/ton of ore	1.1	1.2	1.3	1.1
Recovery, pct:				
Gold	0	75.0	75.0	74.0
Silver	28.6	57.5	63.8	62.9

[1]Cyanide content of the pretreatment solution; total cyanide per ton of ore was the same for all samples.

[2]Flow rate taken as the flooded column drained.

Particle agglomeration was very effective in increasing percolation rates and silver recovery. The flow of leaching solution stopped completely after 22 days in the baseline experiment because the migration of fines during leaching blinded the leaching column. Vat leaching did not increase silver recovery or decrease the leaching time compared to heap leaching agglomerated feed. Particle agglomeration is the only process technology currently available for exploiting this ore. The operators of the property are building facilities for particle agglomeration-heap leaching.

These tests have shown that particle agglomeration techniques have varied effects on different feed material. In all cases evaluated, particle agglomeration provided definite advantages over conventional heap leaching technology. In some of the examples described, particle agglomeration was the only viable processing technique for recovering the precious metal values contained in the ores.

PILOT-SCALE COLUMN PERCOLATION LEACHING EXPERIMENTS

A series of pilot-scale column percolation tests was conducted on the gold ore from the Alligator Ridge district near Ely, Nev. A 5-ton sample of the ore was crushed to 85 pct minus 3/8 inch, blended, coned, and quartered several times to obtain head samples. Two head samples were taken, one for fire assay and the other for a screen analysis.

Results from the fire assay showed that the sample contained 0.11 oz/ton Au. Gold distribution obtained in the screen analysis of the 30-lb head sample is shown in table 8. Table 8 shows that the gold is concentrated in the

minus 10-mesh fractions, and indicates that control of these fines during loading and leaching of a heap is very important. Proper heap construction technique was stressed in a paper presented at the 1980 American Mining Congress Convention in San Francisco, Calif.[9]

TABLE 8. - Screen analysis of the head sample from the Alligator Ridge deposit

Product size	Wt-pct	Gold	
		Assay, oz/ton	Distribution, pct
Plus 3/8 inch...............	15.1	0.04	5.4
Minus 3/8 plus 1/4...........	14.2	.06	7.7
Minus 1/4 inch plus 10 mesh..	44.4	.07	28.2
Minus 10 plus 20 mesh........	8.5	.15	11.5
Minus 20 mesh................	17.8	.29	47.2
Composite..............	100.0	.11	100.0

The remaining crushed feed was coned and quartered to obtain two 1.5-ton samples for the pilot-scale column leaching experiments. Two tests were conducted: (1) baseline or conventional column leaching, and (2) particle agglomeration with portland cement and cyanide solution.

The baseline test was performed by bedding 1.5 tons of dry 3/8-inch feed into the fiberglass PDU leaching column. The depth of the ore bed was 12 ft, which gave an apparent ore bulk density of 79.6 lb/ft^3. Leaching solution, containing 0.5 lb of NaCN per ton of solution was applied at a rate of 10 gal/hr ft^2 of cross sectional area. The pH of the solution was controlled between 10 and 11 with addition of NaOH solution. The pregnant solution passed through a series of four columns, each containing 5 lb of activated carbon for adsorption of gold values. Percolation leaching continued until no gold values were detected in the pregnant solution.

The second 1.5-ton sample was agglomerated in batches. The dry feed was mixed with 10 lb of portland cement per ton of ore and was wetted with a solution containing 13 lb of NaCN per ton. The moisture content of the agglomerated feed was 7.7 wt-pct. The agglomerated feed was placed into the leaching column and aged for 72 hr prior to leaching. The depth of the agglomerated ore bed was 12.5 ft, which gave an apparent bulk density of 76.4 lb/ft^3. No reagent other than the portland cement was required to maintain protective alkalinity at a pH of 10 to 11 during leaching. Leaching solution, initially water, was applied to the agglomerated ore bed at a rate of 10 gal/hr ft^2 of cross-sectional area and was recirculated throughout the leaching experiment. One bed volume of leaching solution was 37 gal. Pregnant and barren solution samples were taken after each bed volume of leaching solution had percolated through the ore. The carbon adsorption system was identical to that employed in the baseline experiment.

A screen analysis was run on each leached residue to determine residual gold values. The results are shown in table 9.

[9]Reference cited in footnote 3.

TABLE 9. - Screen analysis of leached residues from the Alligator Ridge deposit

Product size	Wt-pct	Gold Assay, oz/ton	Gold Distribution, pct
BASELINE TEST			
Plus 3/8 inch................	6.8	0.060	14.6
Minus 3/8 plus 1/4 inch......	22.1	.050	39.5
Minus 1/4 inch plus 10 mesh..	43.6	.020	31.0
Minus 10 plus 20 mesh........	13.1	.010	4.6
Minus 20 mesh................	14.4	.020	10.3
Composite..................	100.0	.028	100.0
AGGLOMERATION TEST			
Plus 3/8 inch................	15.2	0.010	13.2
Minus 3/8 plus 1/4 inch......	13.4	.010	11.4
Minus 1/4 inch plus 10 mesh..	43.9	.010	38.6
Minus 10 plus 20 mesh........	11.9	.010	9.6
Minus 20 mesh................	15.6	.020	27.2
Composite..............	100.0	.011	100.0

Table 10 summarizes the leaching data for the two pilot scale column leaching experiments. Gold recovery for the baseline test was less than that for the agglomeration test, even though leaching period was longer. Channeling of leaching solution through the unagglomerated bed probably contributed to the lower recovery. Fines migration was observed in the baseline test, and these fines collected in the carbon columns. Channeling and fines migration were not observed in the material that was agglomerated. Acceptable percolation rates and high gold content in the pregnant solution were observed in both experiments.

TABLE 10. - Leaching data from the two pilot-scale column leaching experiments conducted on a gold ore from the Alligator Ridge deposit

	No pretreatment (baseline)	Particle agglomeration with cement and cyanide solution
Calculated head...........oz/ton Au..	0.10	0.11
Portland cement.......lb/ton of ore..	0	10
Cyanide..........lb/ton of solution..	2.0	[1]13.0
Moisture.....................wt-pct..	0	7.7
Solution application rate gal/hr ft^2..	10	10
Leaching period...............days..	10	3
Cyanide consumption...lb/ton of ore..	1.1	0.7
Gold recovery...................pct..	73.1	90.4

[1]Cyanide content of the pretreatment solution, total cyanide per ton of ore was the same for all samples.

The channeling in the baseline experiment may have been caused by too rapid a pumping rate during leaching. Gold recovery of more than 90 pct was obtained in a parallel laboratory-scale column leach, where migration of fines and channeling were not observed.

The data from these tests show that the gold ore is amenable to heap leaching. Particle agglomeration with portland cement was advantageous in controlling channeling and migration of fines during leaching. Wetting the feed with cyanide solution during agglomeration decreased the leaching time required to obtain maximum gold recovery; thereby increasing the production rate threefold, and decreasing cyanide consumption.

PILOT-SCALE AGGLOMERATION HEAP LEACHING

Pilot-scale tests employing particle agglomeration technology were conducted by several private operators interested in applying the technique to their precious-metal bearing material. Bureau of Mines personnel acted as advisors. The three pilot-scale experiments described were selected because of the diversity of the materials and methods of mechanical agglomeration employed. Feed materials used in the pilot-scale agglomeration heap leaching tests included (1) a gold ore containing few fines and no clays, (2) a clayey silver mine waste material, and (3) a silver-bearing mill tailings.

Gold Ore

The oxidized disseminated gold ore from the Alligator Ridge district near Ely, Nev., that was used in bench- and pilot-scale column leaching tests, was employed. The ore contained no clays and only 15 wt-pct minus 20-mesh material when crushed to 80 pct minus 3/8 inch. Although the ore did not require agglomeration pretreatment to insure adequate percolation rates, the operators wanted to control particle segregation during stacking and leaching of the heap, and to decrease channeling during heap leaching.

The first test was made on 5,000 tons of feed material crushed to 80 pct minus 3/8 inch and agglomerated with water to control the fines while the heap was being stacked.

The feed was prepared by wetting the dry ore with water at the discharge end of the crusher. Partial agglomeration of fines onto coarser ore occurred as it rolled down the sides of the stockpile. Additional agglomeration occurred as the feed was pushed over the edge of the heap and rolled down the heap's sides. The feed material was carefully stacked to prepare the heap in a manner described by Chamberlin.[10]

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[10]Reference cited in footnote 3.

The heap was leached by sprinkling alkaline cyanide solution containing 0.5 lb of NaCN per ton onto the surface. The application rate was 0.18 gal/hr ft^2 of heap area. The leaching solution percolated through the heap and was collected on a water-impervious pad that drained into a plastic-lined pregnant solution pond. The pregnant solution from the pond was pumped through a series of columns containing coconut shell activated carbon to adsorb the gold values. The barren solution was pumped to a plastic-lined pond, where makeup reagents were added, and was recycled to the heap.

The second test was conducted on 2,500 tons of ore crushed to 80 pct minus 3/8 inch. The feed material was transported with a front-end loader from the crushed ore stockpile to a 9-ton weighing hopper (fig. 9). Ten pounds of portland cement per ton of ore was added to the dry ore as it was conveyed from the hopper to a 14-cubic-yard-capacity concrete mixer (fig. 10). Cyanide solution containing all the required NaCN was introduced into the mixer in three increments. The final moisture content of the 9-ton batches of agglomerated ore was between 7 and 10 wt-pct. Agglomeration of the ore occurred while the concrete mixer transported the treated ore to a stockpile area. The agglomerated feed was transferred from the stockpile by a front-end loader and dumped over the edge of the heap (fig. 11). The same leaching-carbon adsorption procedure employed in the first test heap was used except that leaching was started with water and no makeup reagents were required. Pertinent leaching data comparing both test heaps are shown in table 11.

TABLE 11. - Leaching data from two pilot-scale leaching experiments on Alligator Ridge ore

	Particle agglomeration with--	
	Water	Cement and cyanide solution
Calculated head........................oz/ton Au..	0.17	0.17
Portland cement.................lb/ton of ore..	0	10
NaCN.......................lb/ton of solution..	0.5	[1]8.0
Moisture.................................wt-pct..	7-10	7-10
Solution application rate..........gal/hr ft^2..	0.18	0.18
Leaching period..........................days..	60	40
Cyanide consumption.............lb/ton of ore..	0.3	0.3
Gold recovery..............................pct..	88	85

[1]Cyanide content of the pretreatment solution; the total amount of cyanide added per ton of ore was the same for both tests.

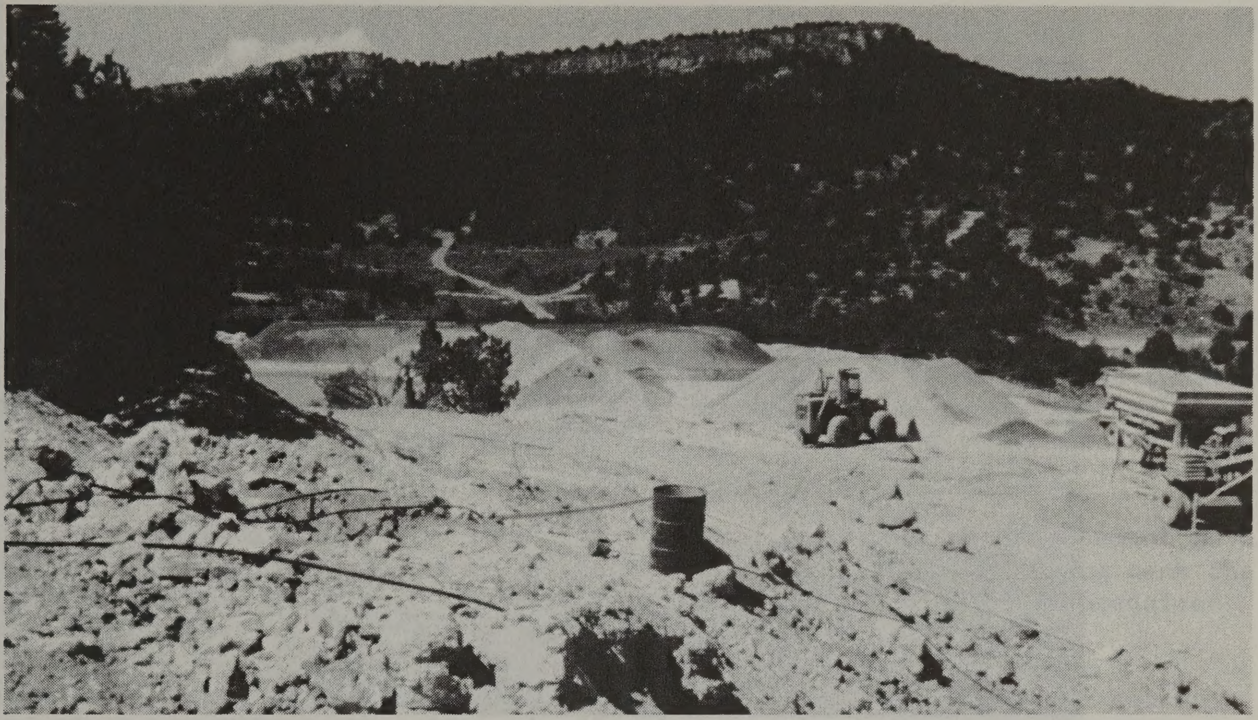

FIGURE 9. - Overall view of pilot-scale agglomeration experiment conducted on gold ore from near Ely, Nev.

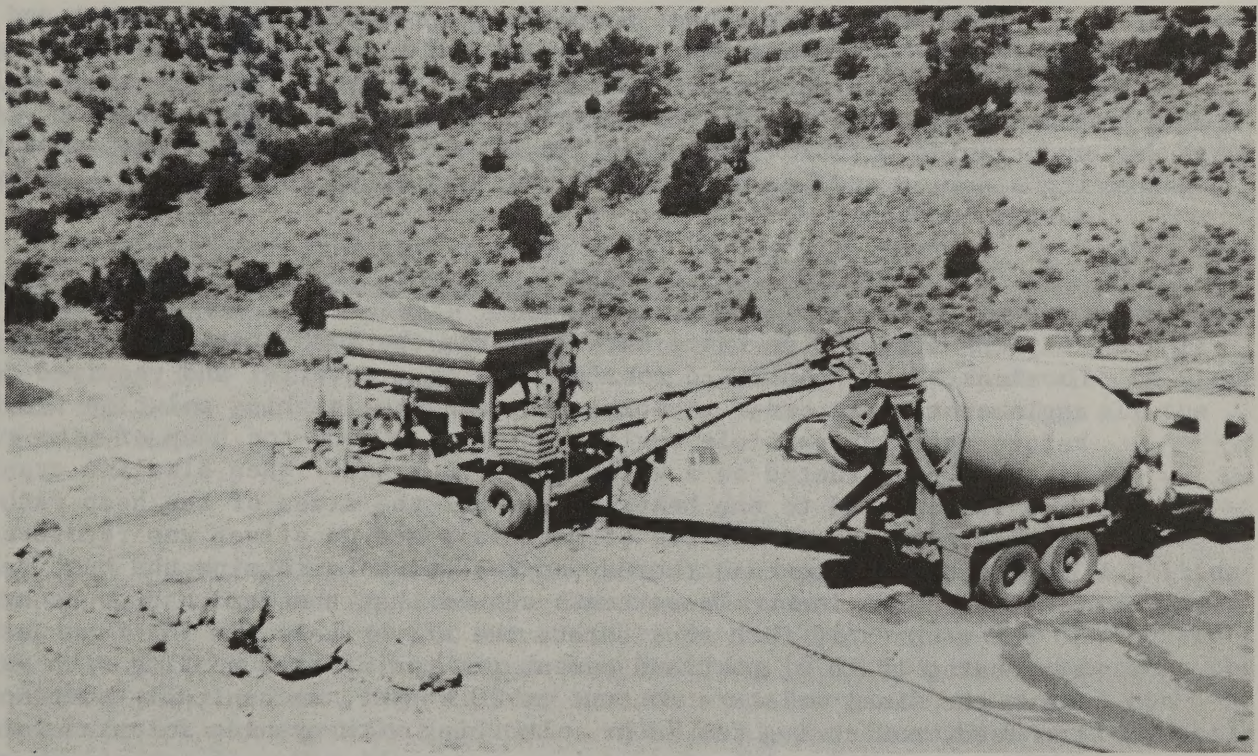

FIGURE 10. - Batch agglomeration equipment from pilot-scale experiment conducted near Ely, Nev.

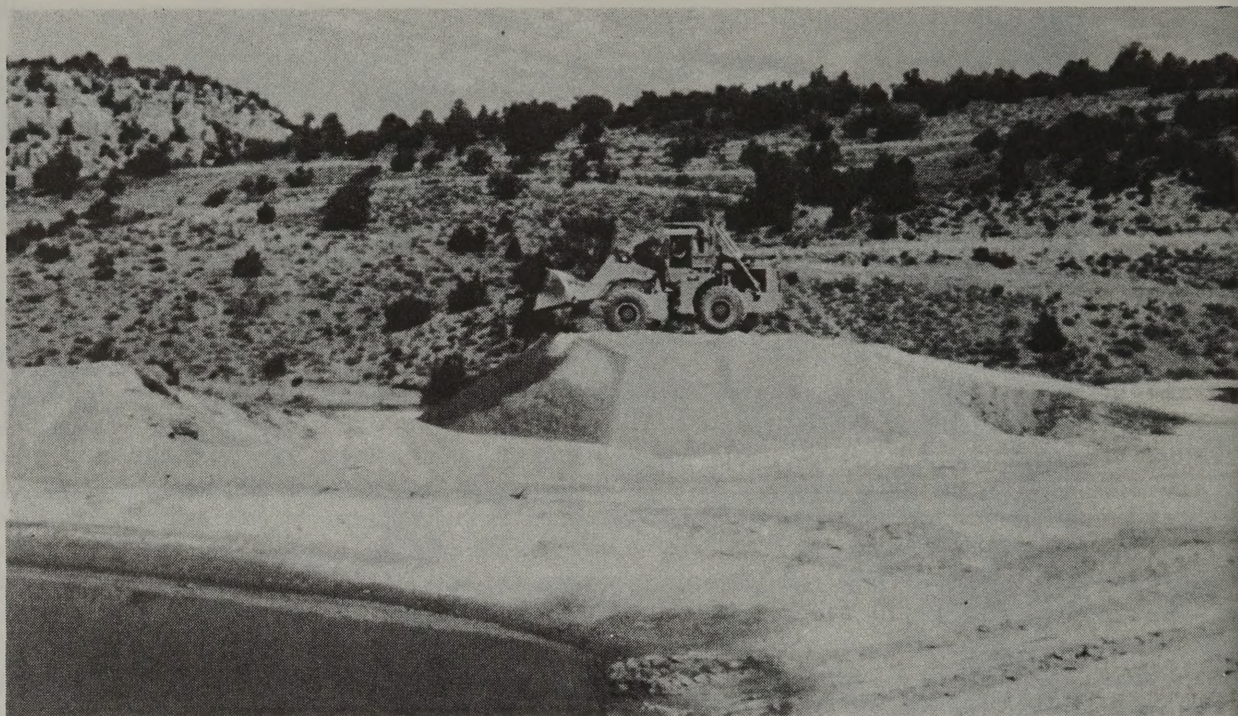

FIGURE 11. - Heap (2,500 tons) agglomerated with cement and cyanide solution under construction near Ely, Nev.

The data indicate that particle agglomeration using cement and cyanide effectively decreased the leaching period required to obtain maximum gold recovery. Gold recoveries were the same as those in bench-scale column percolation experiments. Particle agglomeration with either water or with cement and cyanide solution was effective in controlling the migration of fines during stacking and leaching of the heap and in decreasing solution channeling during leaching.

Silver Mine Waste Material

The silver mine waste material from the Rochester mining district near Lovelock, Nev., contained considerable fine material and required particle agglomeration in order to obtain an adequate leaching solution flow rate. Before applying particle agglomeration, a 30,000-ton heap of mine run waste had been constructed on a water-impervious pad. When alkaline cyanide solution was applied to the heap, it ran off the sides of the heap rather than percolating through the bed of material, and no silver was recovered. Three 300-ton heaps were constructed and leached to determine the best feed size and leaching conditions. These tests showed that the feed had to be crushed to 80 pct minus 9/16 inch to liberate the silver values. The feed was agglomerated using 10 lb of portland cement per ton of ore, wetting with water to bring the final moisture content to 10 wt-pct, mechanically tumbling the wetted feed, and curing for 72 hr. Leaching with cyanide solution for 6 days at a flow rate of 9 gal/hr ft^2 of heap area achieved a 65-pct silver recovery.

Using the agglomeration and leaching conditions determined by these tests, the operators constructed and leached a 1,000-ton heap. Dry material from the original 30,000-ton heap (fig. 12) was transported to a hopper that fed a two-stage roll crusher. The nominal 9/16-inch feed from the crusher was conveyed to the agglomerator (fig. 13).

Agglomeration was accomplished by wetting the crushed feed with 10 pounds of portland cement per ton of feed as a water slurry, the final moisture of the agglomerated feed was between 9 and 11 wt-pct. The moistened feed tumbled down a 4- by 8-ft vibrating inclined chute that contained several "stair steps" to aid agglomeration (fig. 14). Figure 15 shows the agglomerated feed on the leaching pad.

The operators experienced difficulty in applying the portland cement as a slurry. Because of insufficient agitation in the cement-water mixing tank the cement settled and the feed received only one-quarter of the cement required for adequate agglomeration.

Another problem with adding the cement as a slurry was that the cement hydrolyzes rapidly so that it is ineffective as a binder in less than 5 hr. The agglomerated feed was conveyed to a stockpile and later transferred with a front-end loader to a water-impervious leaching pad.

The 1,000-ton agglomerated heap was leached by sprinkling dilute solution over the heap at a rate of 9 gal/hr ft^2 of heap area. The pregnant solution was collected on the water-impervious pad and drained into a plastic-lined pond. Merrill-Crowe zinc precipitation was used to recover the silver from the pregnant solution, the resultant barren solution was recycled to the heap. Sixty percent of the silver in the ore was recovered in 6 days of leaching.

Even with the problems experienced by adding the cement as a slurry, the pilot-scale experiment was successful. Particle agglomeration with portland cement and water was a viable processing technique for this material, whereas conventional heap leaching was not. The operators plan to incorporate this technology into their commercial operation. However, dry cement will be mixed into the feed, and the mixture moistened with a solution containing all the required NaCN.

Silver Mill Tailing

The third application of pilot-scale field testing was to a mill tailing containing 2.5 oz/ton Ag, from the Comstock district near Virginia City, Nev. The tailing, which was 65 pct minus 200 mesh, had been exposed to weathering for several decades. Conventional heap leaching could not be used because the material was too fine. The tailing was also too low grade to warrant construction of a conventional agitation cyanide plant. Several laboratory-scale agglomeration experiments gave encouraging results, which prompted the operators to decide to treat 40 tons of the tailing.

The feed was placed into a hopper and screw fed to a rotating drum 42 inches in diameter and 7 feet long. Thirty pounds of portland cement

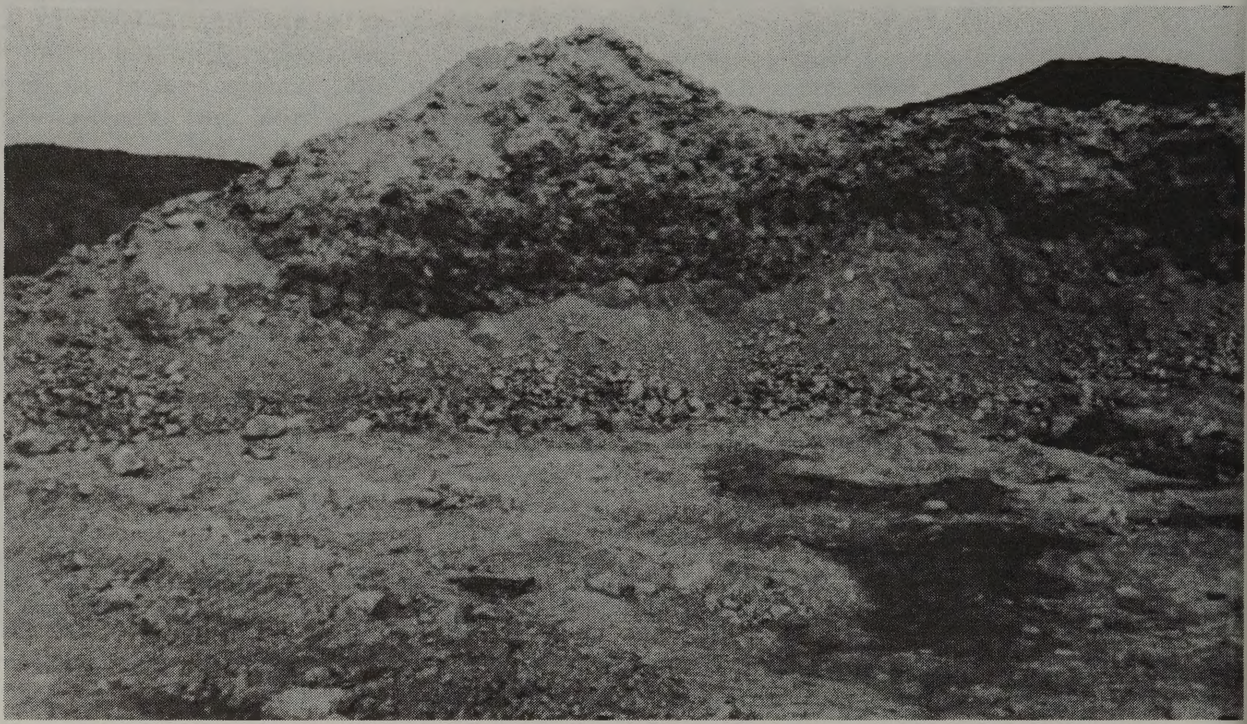

FIGURE 12. - Silver-bearing mine waste material (30,000 tons) on heap before agglomeration.

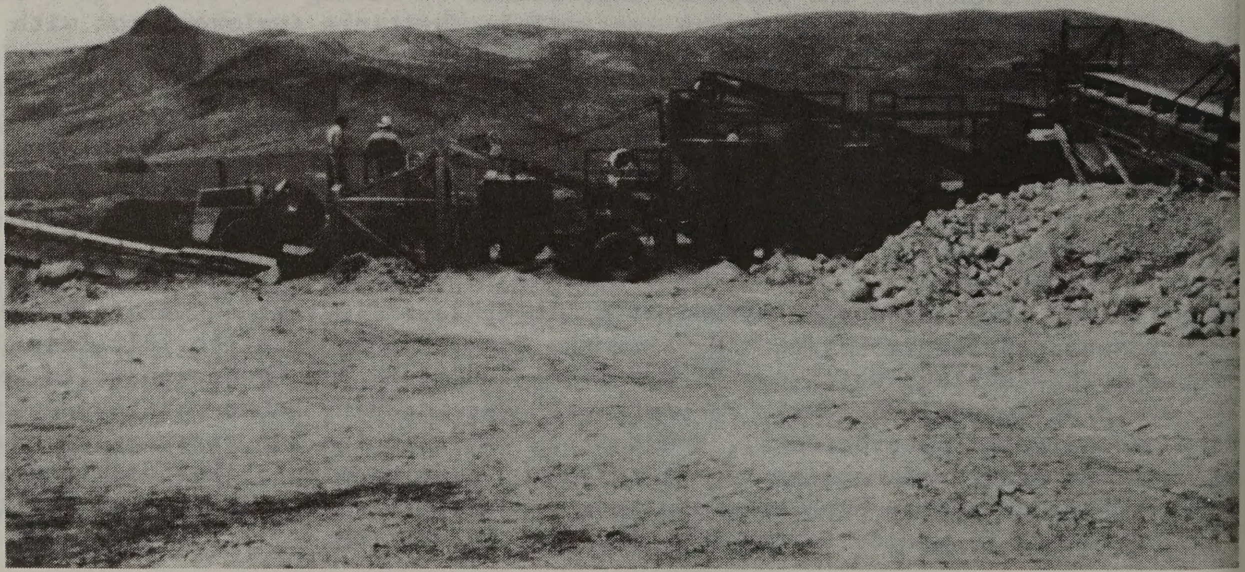

FIGURE 13. - Overall view of pilot-scale crushing and agglomerating equipment from experiment conducted near Lovelock, Nev.

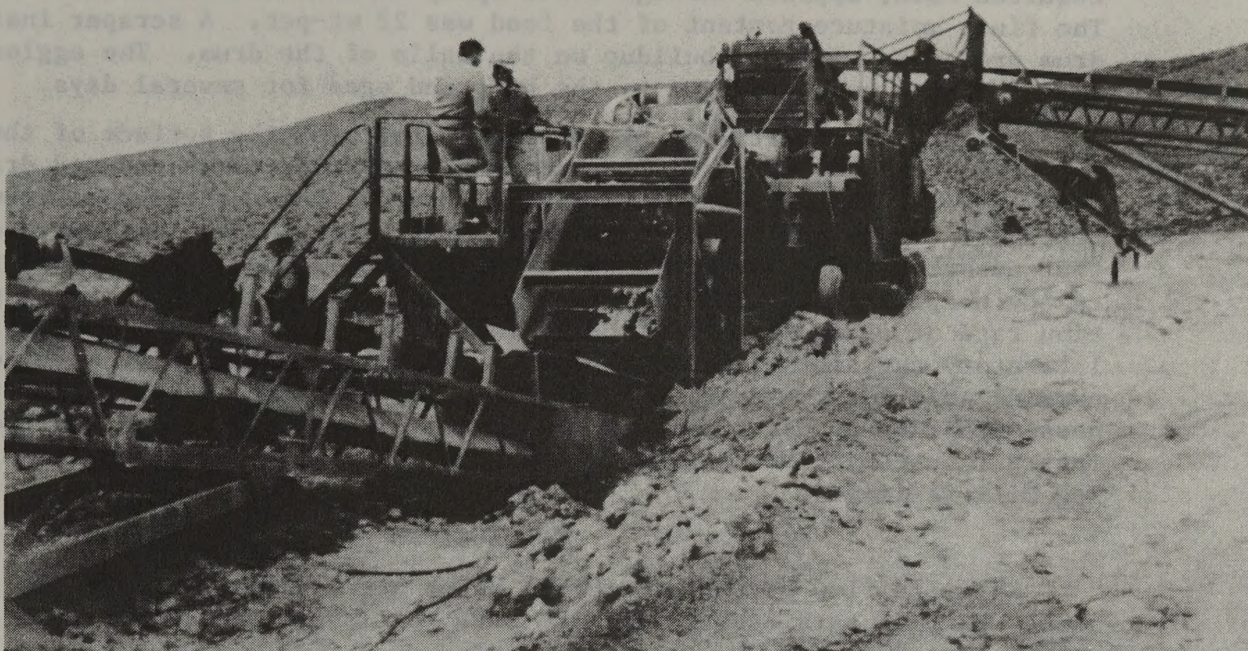

FIGURE 14. - View of agglomerator used in pilot-scale agglomeration experiment conducted near Lovelock, Nev.

FIGURE 15. - Agglomerated feed for the 1,000-ton pilot-scale heap leaching experiment near Lovelock, Nev.

per ton of feed was mixed with the tailing at the discharge end of the screw feeder. The mixture was moistened with cyanide solution containing the required NaCN, applied through three spray nozzles mounted inside the drum. The final moisture content of the feed was 22 wt-pct. A scraper inside the drum prevented material buildup on the walls of the drum. The agglomerates from the drum were conveyed to the heap and aged for several days.

Leaching was initiated by spraying water over the surface of the heap. The pregnant solution was collected on a water-impervious pad and drained into a reservoir. The pregnant solution was pumped from the reservoir upward through a series of five columns containing coconut shell activated carbon that adsorbed the silver values. The resultant barren solution was recycled to the heap. Silver recovery was 78 pct in 5 days of leaching at a percolation rate of 12 gal/hr ft^2 of heap area. Silver recovery was 81 pct in the laboratory agglomeration experiments. Particle agglomeration with cement and cyanide solution was an effective processing technique for this material which possessed poor percolation characteristics. The operators of the property intend to use particle agglomeration-heap leaching to process the silver bearing mill tailing.

CONCLUSIONS

Solution flow rates through ore heaps are greatly increased by agglomerating the fine particles in the ore with portland cement, water, or cyanide solution, and curing.

Several potential benefits can be attributed to particle agglomeration as a pretreatment before heap leaching:

- Clayey and finely crushed ores can be treated by low-cost heap leaching procedures. This permits treatment of low-grade ore bodies, many of which are presently considered submarginal for a cyanide process.

- Increased precious metal recovery from an ore can be realized because additional values can be liberated by finer crushing without particle segregation during preparation and leaching of ore heaps. Particle segregation in unagglomerated materials can cause localized accumulations of fines that inhibit flow of leaching solutions.

- Channeling of leaching solution through the agglomerated ore bed is minimized; thereby, decreasing the leaching period required to obtain maximum precious metal recovery.

- Percolation rates are increased; thus, decreasing the time required for each leaching cycle. This means an increase in production rate and mine capacity without increasing capital cost for pad preparation.

- The highly porous nature of the agglomerates permits the heaps to "breathe;" thereby, providing the oxygen necessary for gold dissolution. The height of the heap can be increased so that the pad preparation cost per ton of ore processed is less, and land area is more effectively used.

- It is assumed that favorable environmental conditions may be realized because the highly porous structure of the heap permits efficient washing of residual cyanide from leached heaps. The stable agglomerates presumably minimize dusting problems when the heaps are abandoned.

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